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Topology control of tactical wireless sensor networks using energy efficient zone routing

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Abstract
The US Department of Defense (DoD) routinely uses wireless sensor networks (WSNs) for military tactical communications. Sensor node die-out has a significant impact on the topology of a tactical WSN. This is problematic for military applications where situational data is critical to tactical decision making. To increase the amount of time all sensor nodes remain active within the network and to control the network topology tactically, energy efficient routing mechanisms must be employed. In this paper, we aim to provide realistic insights on the practical advantages and disadvantages of using established routing techniques for tactical WSNs. We investigate the following established routing algorithms: direct routing, minimum transmission energy (MTE), Low Energy Adaptive Cluster Head routing (LEACH), and zone clustering. Based on the node die out statistics observed with these algorithms and the topological impact the node die outs have on the network, we develop a novel, energy efficient zone clustering algorithm called EZone. Via extensive simulations using MATLAB, we analyze the effectiveness of these algorithms on network performance for single and multiple gateway scenarios and show that the EZone algorithm tactically controls the topology of the network, thereby maintaining significant service area coverage when compared to the other routing algorithms.

1. Introduction

A Wireless Sensor Network (WSN) is a group of autonomous sensor nodes that are geographically distributed to gather data and monitor events. WSNs are finding increased applicability to the Department of Defense (DoD) in areas specific to surveillance and reconnaissance. A tactical WSN is used in a remote geographic location in order to monitor deployed systems and trigger alerts at a Command-and-Control (C&C) site when

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certain events occur. Each sensor node in the WSN must have the ability to simultaneously serve as a sensing device and a wireless communication device that can exchange information with nearby nodes [1]. The gateway serves as the destination for a node's packets is the bridge between the tactical WSN and the backbone infrastructure which includes the C&C site. Because the gateway is a significant component of the WSN architecture, its location must be considered. We focus our attention toward gateway locations on the periphery of the sensor field. For tactical WSNs, we assume that a location on the periphery is more likely to be a safe zone compared to where the sensor nodes are deployed. Our use of safe zone refers to a location where the gateway is outside normal environmental and physical constraints to which sensor nodes may be subjected.

In this paper, we investigate two types of tactical WSNs: (1) a single gateway scenario and (2) a multi-gateway scenario. The majority of existing research on WSNs generally includes the perspective of a single gateway [1-5]. The few works that study multigateway sensor networks focus on reliable routing, not taking into consideration the energy efficiency requirements of the sensor nodes [6,7]. Thus, it is important to extend WSN concepts to a multi-gateway framework and identify the resulting performance improvements by including an additional gateway.

1.1. Deployment challenges of tactical WSNs

A tactical WSN must operate reliably and increase sensor network coverage for as long as possible in the absence of human contact. A key challenge in the deployment of tactical WSNs is the limited battery power of each sensor node. This has a significant impact on the service life of the network. We define service life of a tactical WSN to be the amount of time that nodes are able to transmit information to the gateway without significant interruption. The service life of the network is contingent upon the network topology. As nodes begin to die out, the remaining live nodes may be disconnected from one another, undermining their ability to communicate with the gateway node. For example, if only 20% of the nodes in the network remain alive (i.e., have enough residual energy to use for transmitting, sensing and/or receiving), but they are concentrated within transmission range one another, then communications can still take place for that area. This is the preferred situation. However, with 80% of the nodes dead, the possibility of live nodes residing in areas where they are detached from one another is also possible. While this situation may also occur in a commercially used WSN, the ramifications of information not getting to the gateway may not be as severe as in a tactical WSN where important information from the battlespace is being transmitted from the sensor nodes and being used for tactical decision making. Thus, the ability to control the network topology using an effective routing algorithm is essential to ensuring that the network remains usable for the longest amount of time. In this paper, topology control refers to the ability of the routing algorithm to ensure that nodes with residual energy in one or more areas remain connected to one another and/or the gateway for continued data transfer.

1.2. Motivations and contributions

Energy efficient routing is not a new topic in WSN research. Extensive studies have been conducted in this area [1,2,8-14]. Many of these works offer modifications to already well established WSN routing algorithms. Both [12] and [13] provide algorithms for the modified Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm [2]. In addition, [10,11,14] and [15] develop algorithms based on the idea of clustering. Clustering is a common hierarchical routing procedure implemented in WSNs. The idea is that energy consumption is reduced by allowing only a select number of nodes, known as Cluster Heads (CH), to aggregate data from member nodes and transmit to the gateway. A disadvantage with clustering is the CH election process. Depending on the type of procedure used, CHs may be elected such that they reside on the opposite end of the network [16]. This situation is common in LEACH where CHs are elected randomly based on a probability model. This means that an elected CH may not be physically close to node members. This then nullifies any energy savings that clustering achieves. There have been various modifications to LEACH in recent years, including improvements to LEACH security [17]. However, the fundamental CH election procedure remains the same, exposing the problem of CH election as mentioned above.

There has been some work that has been done on tactical WSNs that serve as a foundation for our work [18,19]. While [18] and [19] provide architectural constraints for tactical WSN deployment, the routing process and its impact on network topology is not discussed. In [20], the authors develop a cross layer load balancing/routing scheme for tactical WSNs. However, the authors do not provide an in depth analysis on the impact of tactical topology control when using load balancing and routing algorithms.

In this paper we show traditional routing algorithms that are regularly used in commercial WSNs have a negative impact on the service life of a tactical WSN because their design is not meant to meet the requirements of tactical WSN applications. More specifically, we extend our work in [20] by showing that established routing algorithms regularly seen in the literature do not effectively control the topology of the network. We aim to provide realistic insights on how an energy efficient routing algorithm can increase service life by tactically controlling the network topology. To the best of our knowledge, this is the first work to provide an extensive analysis of how different routing algorithms impact the operational capability of a tactical WSN.

Our contributions in this paper can be summarized as follows:

- Develop a novel energy efficient zone routing algorithm that tactically controls the network topology. We call this algorithm EZone. We identify performance improvements of EZone and compare it to the following established routing techniques: (1) Direct Routing, (2) Minimum Transmission Energy (MTE), (3) Low Energy Adaptive Clustering Hierarchy (LEACH), and (4) Zone routing. We also identify performance improvements of adding an additional gateway to these algorithms.
- As sensor-node battery levels are depleted and nodes subsequently die out, we show how EZone affects the topology of live nodes and dead nodes in the sensor field

and how this affects the continuous service coverage throughout the sensor field. We compare EZone service life with the network service life obtained using each of the four routing algorithms mentioned above and show EZone's ability to tactically provide continuous service.

The remainder of this paper is organized as follows. In Section 2, we discuss the models implemented at each layer of the tactical WSN protocol stack. In Section 3, we discuss the EZone algorithm and its implementation. Ezone is compared with four traditional routing algorithms that are also described. We provide our simulations and analysis of the results in Section 4. We conclude the paper in Section 5.

2. Tactical WSN protocol stack implementation

We implemented the following models into each layer of the protocol stack.

Physical layer: All nodes in our simulations begin with a starting energy level of 0.5 Joules (J). This is a value commonly used in the literature because it provides small enough energy to quickly see the effects of the varying algorithms involved yet it provides enough energy to demonstrate node life longevity by making algorithmic improvements.

The physical model relates to the amount of energy a sensor node consumes during transmit and receive operations. Several power energy consumption models exist in the literature [21-24]. Each model presents a different way of calculating total energy consumption for different sensor nodes. We chose to utilize a first order power amplifier and sensor model for simplicity and because it is more prevalently used in the literature [2,25,26]. This model assigns an energy cost-per-bit to collect, transmit and receive information. It considers direct path and multi-path wireless signal propagation theory to identify the amount of information required to transmit one bit of information over a certain distance between nodes while guaranteeing adequate signal-to-noise (SNR) ratio at the receiving node. We utilize the first order radio energy model to relate the energy expended to send and receive an L-bit message over a distance d when considering direct path and multi-path propagation [1,2,16,27].

The energy expended in the transmit electronics for free space (direct path) propagation, E_{Tx-fs}, is described by

$$E_{Tx-fs}(L,d) = E_{Tx-elec}(L) + E_{Tx-amp}(L,d) = E_{elec}L + \varepsilon_{fs}Ld^2 \quad (1)$$

and for multipath propagation by

$$E_{Tx-mp}(L,d) = E_{Tx-elec}(L) + E_{Tx-amp}(L,d) = E_{elec}L + \varepsilon_{mp}Ld^4 \quad (2)$$

where E_{elec} corresponds to the energy per bit required in transmit and receive electronics to process the information, E_{Tx-amp} is the electrical energy required to transmit an L-bit message over a distance d, and ε_{fs} and ε_{mp} are constants corresponding to the energy per bit required in the transmit amplifier to transmit an L-bit message with adequate SNR over a distance d^2 and d^4 for free space and multi-path propagation modes, respectively.

The energy expended to receive the L-bit message in the receive electronics is described by

$$E_{Rx}(L) = E_{elec}L \quad (3)$$

The corresponding values from Eqs. (1)-(3) for the amplifiers and electronics used in our subsequent simulations are described in Table 1.

Table 1 Radio energy dissipation parameters [4].

Constant	Value
Transmit and receive electronics, E_{elec}	50 nJ/bit
Transmit amplifier, free space propagation, ε_{fs}	10 pJ/bit/m^2
Transmit amplifier, multi-path propagation, ϵ_{mp}	0.0013 pJ/bit/m^4

MAC layer: We simulate the MAC layer simply through the performance of transmission rounds. Each simulation begins at round one and ends when the last node dies. During each round, each node in the WSN sends an L bit packet to the gateway. We implement a Time-Division Multiple Access (TDMA) scheme that assigns each node in the WSN a timeslot during each round. The node transmits information to the gateway during the timeslot. With the clustering and zoning algorithms, we assume that the MAC process is similar to that described for LEACH, in which CHs are assigned a TDMA timeslot for transmission to the gateway and CHs are assigned Code-Division Multiple Access (CDMA) schemes for intra-cluster communications to prevent interference with other clusters/zones.

Network layer: There are a variety of routing algorithms applied to the network layer in the literature, some of which are described in [3,5,4,28,29]. We implement several traditional and established routing algorithms observed in the literature. We also develop and implement our own energy efficient routing algorithm (EZone). The routing algorithms we implement are direct, MTE, LEACH, zone, and EZone. We will discuss these algorithms in further detail in Section 3.

Transport layer: Our transport layer implements User Datagram Protocol (UDP).

Application layer: Our application layer implements two strategies: (1) use of a traffic generator, and (2) use of a data aggregation technique. The traffic generator of each node generates a 2000 bit data message during each round for transmission to the gateway. Data aggregation is used only for the clustering and zone routing algorithms and the CH is the only node that can perform data aggregation. The CH receives all the messages from nodes in the cluster. It then includes its own message, compresses all the messages into one 2000-bit message, and transmits the compressed message to the gateway at the end of each round.

Data aggregation requires energy to perform the signal compression, which must be accounted for. We adopt a similar technique used in the literature, which applies an energy cost to the data aggregator for the task of aggregating all the data during a round. A data aggregation constant, EDA (event oriented data aggregation), is used to account for the energy to compress messages into one final $L=2000$ bit message. The data aggregation constant used in our scenarios is consistent with the literature (EDA=5 nJ/bit) and results in an aggregation cost of $EDA \times L$ [1,2,27,30,31].

3. Routing algorithms for tactical WSNs: traditional vs EZone

In this section, we describe the five routing algorithms that were simulated: direct, MTE, LEACH, Zone, and EZone.

3.1. Traditional routing algorithms: direct, MTE, LEACH and zone

Direct transmission to the gateway involves each node sending a packet to the gateway directly without using any other nodes along the way. During each round, the Euclidean distance is calculated between the node and the gateway. The distance along with the transmit amplifier parameters given in Table 1 is used to determine the propagation mechanism [16]. The node's energy is decremented in proportion to the required energy for packet transmission to the gateway.

In MTE routing we minimize the propagation distance to the gateway in order to produce a route that minimizes the overall sensor energy depletion rate. We utilize propagation distance as our link cost parameter to input into the MTE algorithm. We use Dijkstra's algorithm to generate our MTE routes. In MTE routing, the node closest to the gateway is always chosen to be included in the route. This node is known as the hot node. Since the hot node is the relay point between the gateway and all traffic from other nodes, it is overwhelmed with traffic during each round and dies quickly. Another hot node is then immediately chosen. This hot node concept in MTE routing causes nodes that are closest to the gateway to die out first.

The LEACH algorithm is a well-known clustering algorithm developed specifically for WSNs. LEACH routing elects one or more CHs and nodes associate with the nearest CH. The role of CH is rotated among the nodes in the following way: each node picks a random number between zero and one. Each node also computes a threshold number (T_n), which is a number between zero and one and is proportional to the current round. The probability for any node to serve as a CH is denoted as p. If a node has been a CH in the last $\frac{1}{p}$ rounds, it is excluded from being a CH during the round. Otherwise, if the temporary random number is less than T_n, the node is elected as a CH during the round. The desired probability for a node to be chosen as a CH is an input to the algorithm and must be specified. The original authors of LEACH performed analysis to determine the optimum value for p to be 0.05 [1]. Each node transmits its data message to its CH. Each CH collects all the messages of its nodes and retransmits them collectively to the gateway. This process repeats during subsequent rounds until all nodes have died.

Zone clustering appears less frequently in the literature as compared to LEACH. However, for a tactical network, it may be a preferred routing algorithm because the user can specify how zones are characterized for the network. The general methods used for the zone routing algorithm are based on techniques described in [8]. In [8], the authors utilize a sensor field comprised of homogeneous zones. Partitioning the network in zones essentially creates several smaller WSNs that all utilize the same gateway. A sensor in each zone has a probability p of becoming a CH during each round. The probability p is determined to be relative to the number of nodes in the zone: $p=\frac{1}{(\text{number of nodes in zone})}$. The zone clustering algorithm divides the sensor field into z equal zones. Equal zones span along the Cartesian x-axis to create z vertical rectangular zones. We use five zones in our simulations. Five zones were chosen to provide a comparison with the LEACH algorithm. Recall that in the LEACH algorithm, the probability of any node being chosen as a CH is $p=0.05$. Thus, in a 100 node network, we would have five CHs. To ensure that there are five CHs for our zone clustering algorithm, we must have five zones and each zone is only allowed to have one CH.

During each round, the set of live nodes for each zone is identified, and the CH is chosen based on a random assignment from this set. Each node in the zone then transmits its L-bit packet to the zone's CH and its energy is decremented according to our radio energy model. The CH for the zone then aggregates all the messages from the nodes in the zone and transmits the aggregated message to the gateway.

For all four routing algorithms discussed in this section, the multigateway scenarios operate the same way as described, except the gateway that is closest to each node in terms of Euclidean distance is chosen to receive data.

3.2. EZone: zone clustering with energy efficient cluster head selection

The zone clustering case described in Section 3.1 chooses the CH for each zone randomly. A clustering algorithm that partitions nodes into specific zones is an energy saving technique when compared to the LEACH algorithm because there is a lower maximum distance that any node must transmit to reach its CH. Zone routing guarantees a nearby CH in the zone as compared to that of LEACH. In LEACH the nearest CH may be on the other side of the network since the criteria for a node to be elected as a CH may have only been met randomly on the other side of the field [16].

There are significant differences in energy distribution of the nodes in the network. The differences in energy levels across the WSN cause some nodes to die out earlier and some nodes to die out later. Therefore, in the EZone algorithm, we modify the CH election criteria in the following way: in any given round, if the highest energy node is chosen to be the CH, individual node energy depletion rates are decreased allowing battery levels in any zone to deplete at a uniform rate.

To accomplish this strategy, the zone routing algorithm is revised. Instead of randomly choosing the CH from the live nodes in the zone, we choose the CH that has the maximum energy level in the zone. Based on this election criterion, nodes that are in a more preferred location (a location that decreases energy depletion rate such as locations closer to the gateway) are chosen to be the CH for the zone more than those in a less preferred location (a location farther away from the gateway).

The EZone algorithm is executed in three phases: (1) network setup; (2) CH election for each zone; and (3) packet transmission from CH to gateway. The network setup phase creates the WSN and partitions the network into the required number of zones. The number of zones is based on user requirements and application scenario. We use 5 zones to facilitate comparison with the zone routing algorithm using random CH election given in [8]. Partitioning the network into zones effectively creates several smaller WSNs that all utilize the same gateway. The zone assigned to any node is based on the node's x-coordinate in the network field. Once all nodes are assigned to a zone, we begin the simulation at round one. In each round, the set of live nodes for each zone is identified and the CH is elected based on highest node energy.

Electing the highest energy node to be the CH during each round in each zone requires additional processing by the gateway to perform CH election. In order for the gateway to make an effective CH choice for each zone, it must be aware of all the alive nodes in each zone and the residual energy (remaining energy) of each alive node. Each node in the zone maintains a power meter that is used to maintain node residual power. Each alive node in each zone decrements its power meter each time it transmits a packet to the clusterhead of that zone. The decrement is based on the radio energy model given in Eqs. (1) and (2). All alive nodes communicate with the gateway during the start of each round. During round 1 only, the gateway chooses the CH randomly, similar to [8]. The reason the CH is chosen randomly for round 1 is because it is assumed that at the start of the algorithm all nodes have equal energy and thus any node can be the CH. The CH of round 1 transmits an aggregated packet to the gateway. The aggregated packet includes the residual node energies for each alive node in the zone (including the current CH) in the packet header. The gateway uses the residual power values to choose the CH for each zone for the next simulation round. The node with the highest residual energy is chosen by the gateway to be the CH for the subsequent round. The CH choice is then broadcast back to each zone. Once a CH is elected by the gateway, the CH maintains its power meter by (1) decrementing the energy required to aggregate and send the packet for that round to the gateway based on the radio energy model and (2) decrementing the energy cost for the CH to receive packets from nodes in its zone. The decrement is calculated based on Eq. (3).

This CH selection based on highest node residual energy is a minor adjustment from the traditional zone routing algorithm but it has a significant effect on the service life and network topology of a tactical WSN, as will be shown in Section 4.

4. Simulations and result analysis

In our simulations, sensors and gateways are all placed on a Cartesian grid with axes x and y. Our simulations and analysis involve a grid of 100 sensors such that each sensor's x and y coordinate is modeled as a uniformly distributed random variable between 0 and 50 meters (m). The single gateway scenario employs the gateway at $(x, y)=(25\text{ m}, -100\text{ m})$. In the multigateway scenario an additional gateway is placed at the position (25 m, 150 m). In the subsequent figures, gateways are displayed as solid green nodes and live nodes are represented by a blue outline circle. We show the perimeter and zone fields as solid red lines. All nodes have a starting energy of 0.5 J, except the gateway (s) which is assumed to have unlimited energy (they are not energy constrained). The traffic routed in the network is generated using a Constant Bit Rate (CBR). The size of each message (L) is 2000 bits.

All our simulations assume that each node is within wireless transmission range of the gateway which also means that each node is within communication range of any other node in the WSN. We make this assumption in order to simplify the simulation scenario. This simplification makes it easier to analyze node-die out statistics and network topology characteristics for each routing algorithm executed. In our future work, we will loosen this assumption. All our simulations were executed in MATLAB.

4.1. Topology control analysis of routing algorithms: traditional vs EZone

In every round we generate several plots to characterize energy consumption and the distribution of live and dead nodes in the network. We produce three plots during each round. The first plot is a bar plot that provides the energy of each node from 1 to 100 where node 1 is the closest node to $x=0$ (the y-axis) and node 100 is on the other side of the sensor field closest to the line $x=50$ m. The second plot is a three-dimensional energy stem plot where each stem is located in the position of the node in the field, and the height of the stem represents the amount of residual battery energy available. The energy stem plot is green, and the elevation (energy level) decreases during each round, corresponding to energy consumption. When the stem reaches zero energy (the floor), the green bubble changes to red to indicate the node has died. The final plot is an overview of the sensor field topology including the gateway during a particular round. We refer to the first plot as the energy bar plot, the second plot as the energy stem plot and the third plot as the node distribution plot. The node distribution plot shows live nodes as a circle with a blue outline and dead nodes as solid red bubbles. The node distribution plot also contains the round from which all three plots are drawn. The energy bar and stem plots are stacked on top of each other on the left hand side of the figures, and the node distribution plot is on the right side of the figures. For each simulation, this is plotted four times corresponding to the round the first node dies and the round that 10%, 50%, and 80% of nodes have died. To constrain the length of this paper, we provide the plots for 80% of nodes dead to illustrate the operational mechanism of the direct and MTE routing algorithms. We provide the plots for 10% and 50% of nodes dead to illustrate LEACH and generic zone routing. We provide plots for 10%, 50%, and 80% of nodes dead for the EZone routing algorithm. Due to space, these plots are graphically shown for the single gateway scenario only (in Section 4.2 we provide further discussion on the multigateway scenarios by providing ensemble graphs that show the performance of each routing algorithm in multigateway scenarios). The results depicted in Figs. 1-9 are simulations of one specific topological configuration.

Direct transmission: The plot for 80% of nodes dead is shown in Fig. 1. The energy stem plot demonstrates that

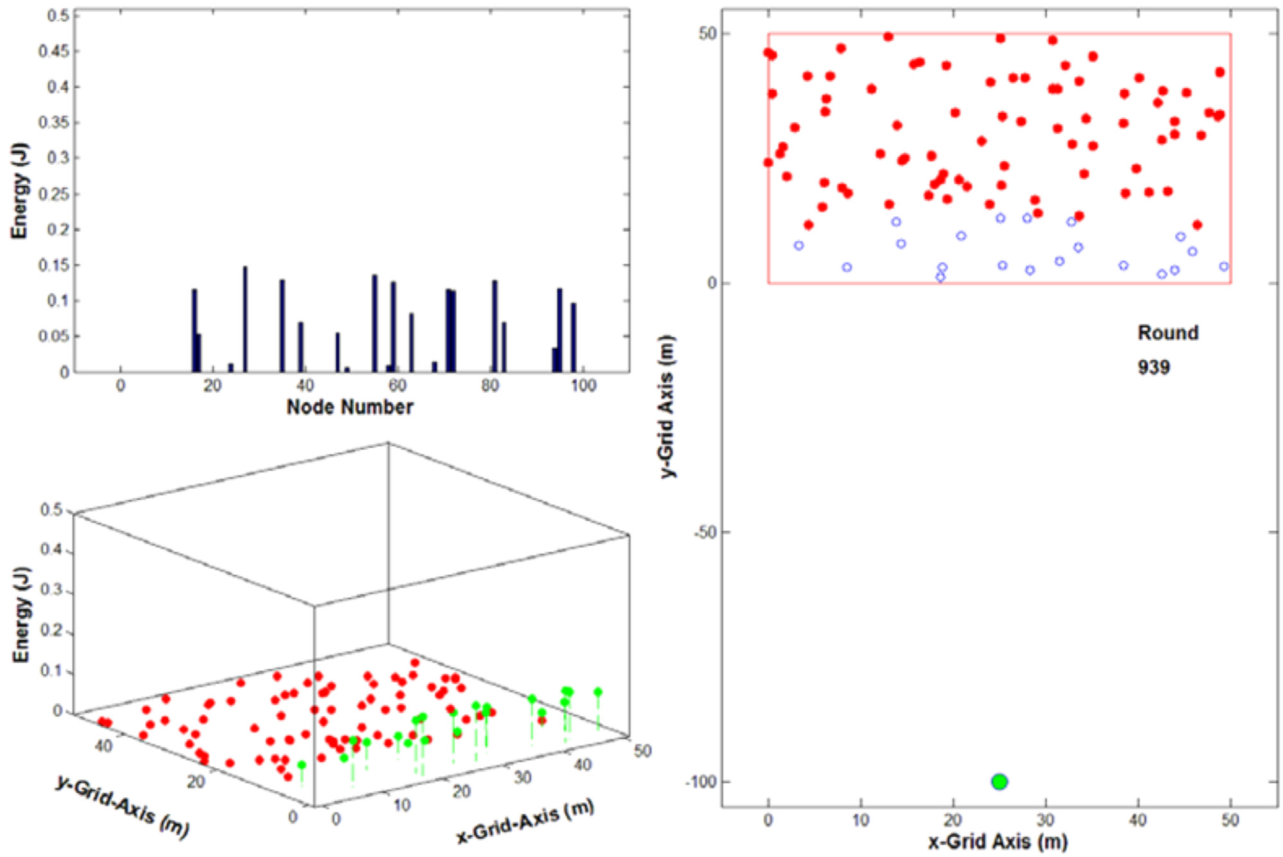

Fig. 1 Illustration of a single gateway tactical WSN for direct routing. The network topology when 80% of the nodes are dead is on the right of each subplot, the energy stem plot is shown in the lower left and the energy bar plot is on the upper left of the subplots.

nodes closest to the gateway remain in service longer than nodes farther from the gateway because our physical layer depletes energy proportional to distance.

MTE with Dijkstra routing: The plot for 80% of nodes dead is shown in Fig. 2. The energy stem plot and node distribution plots demonstrate that nodes closest to the gateway die out first and then fan out as subsequent live nodes closest to the gateway become the hot nodes. As expected, this quickly eliminates service coverage in those areas. Nodes that are farthest away from the gateway are not used by their peers as frequently for routing, thus their energy is preserved. This creates a large energy variance and the quickest die out for all results collected in this paper (variance results produced by each routing algorithm are further examined in the next section).

LEACH: The 10% and 50% of nodes dead are plotted in Figs. 3 and 4, respectively. The CHs are indicated by a blue asterisk that fills the nodes. Our display of CHs involves one caveat for LEACH and zone routing algorithms. In some cases, the CH asterisk indicator is plotted over with a solid red circle because its energy was fully depleted in its last round as the CH. Our plots are drawn at the end of each round; thus, if a node is dead and it was the CH during the round, it is depicted as a dead node. The energy stem plot and node distribution plots in both figures demonstrate that nodes die out starting in the middle of the network and progress out. From this outward progression, nodes toward the top of the network die out more quickly than nodes at the bottom of the sensor field because nodes at the top use more energy to transmit a cluster's payload to the gateway during the random times they are selected as the CH. Nodes at the center of the field start to die out first as a result of LEACH's mechanism for determining CHs and cluster assignments at each round. Thus, this shows that LEACH inefficiently partitions the sensor field with CHs, without regard to any spatial arrangement.

Zone routing: The plots for 10% and 50% of nodes dead are shown in Figs. 5 and 6, respectively. The energy stem plot and node distribution plots demonstrate much more uniform energy depletion as compared to all the other algorithms tested thus far. Since any node can be randomly selected to be a CH more than any other node in the network, this creates a random mode for nodes to die out. Zones in the node distribution plots die out consistently with no one zone dying out earlier than another zone. We found that when the zone algorithm is run, the first node dies at round 1649, providing the longest service life of 100% of nodes alive of all algorithms tested thus far. This will be further discussed in the next section.

EZone: We provide plots for the EZone routing algorithm when 10%, 50% and 80% of the nodes die. These plots are shown in Figs. 7-9. The energy stem plot and node distribution plots demonstrate that zones die out from the outer zones in the sensor network, progressing toward the center.

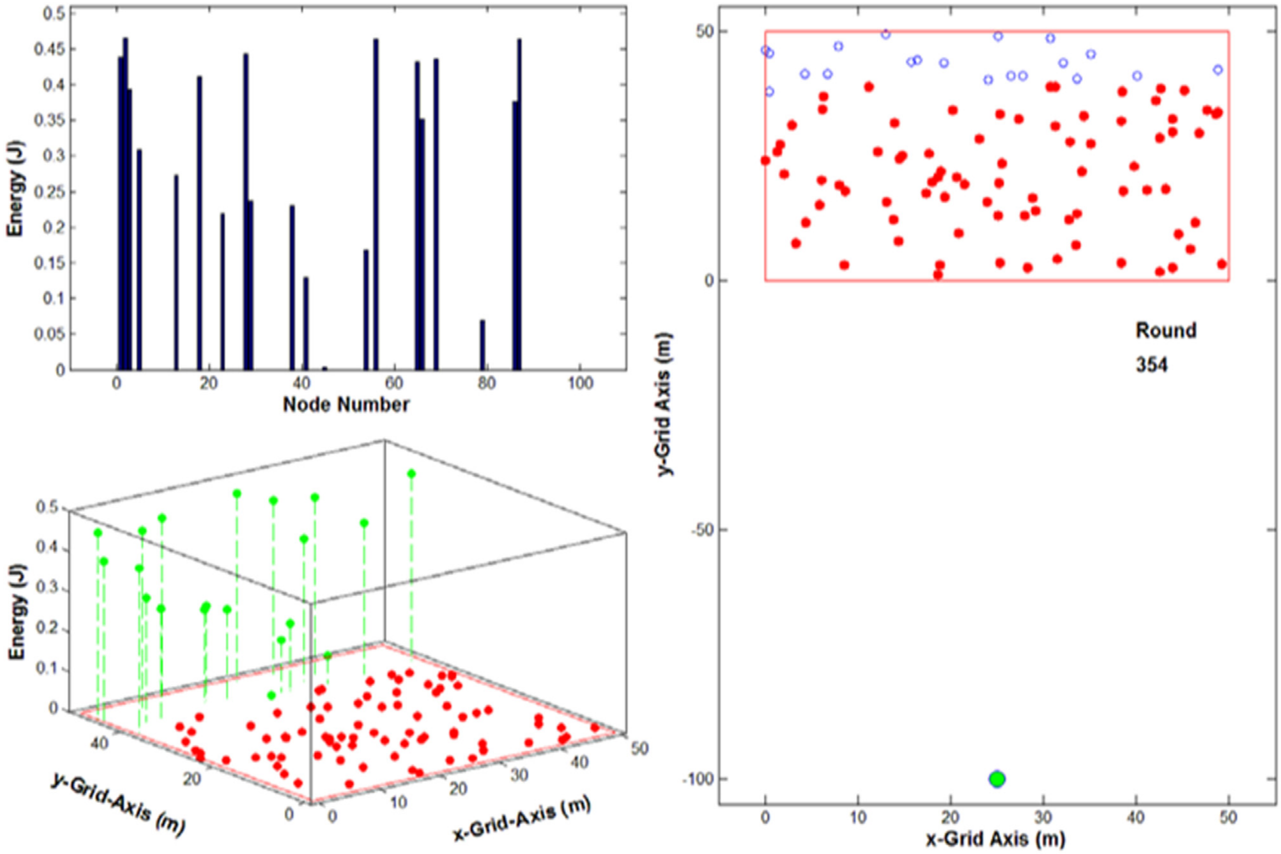

Fig. 2 MTE routing in a single gateway tactical WSN illustrating the network topology when 80% of the nodes are dead.

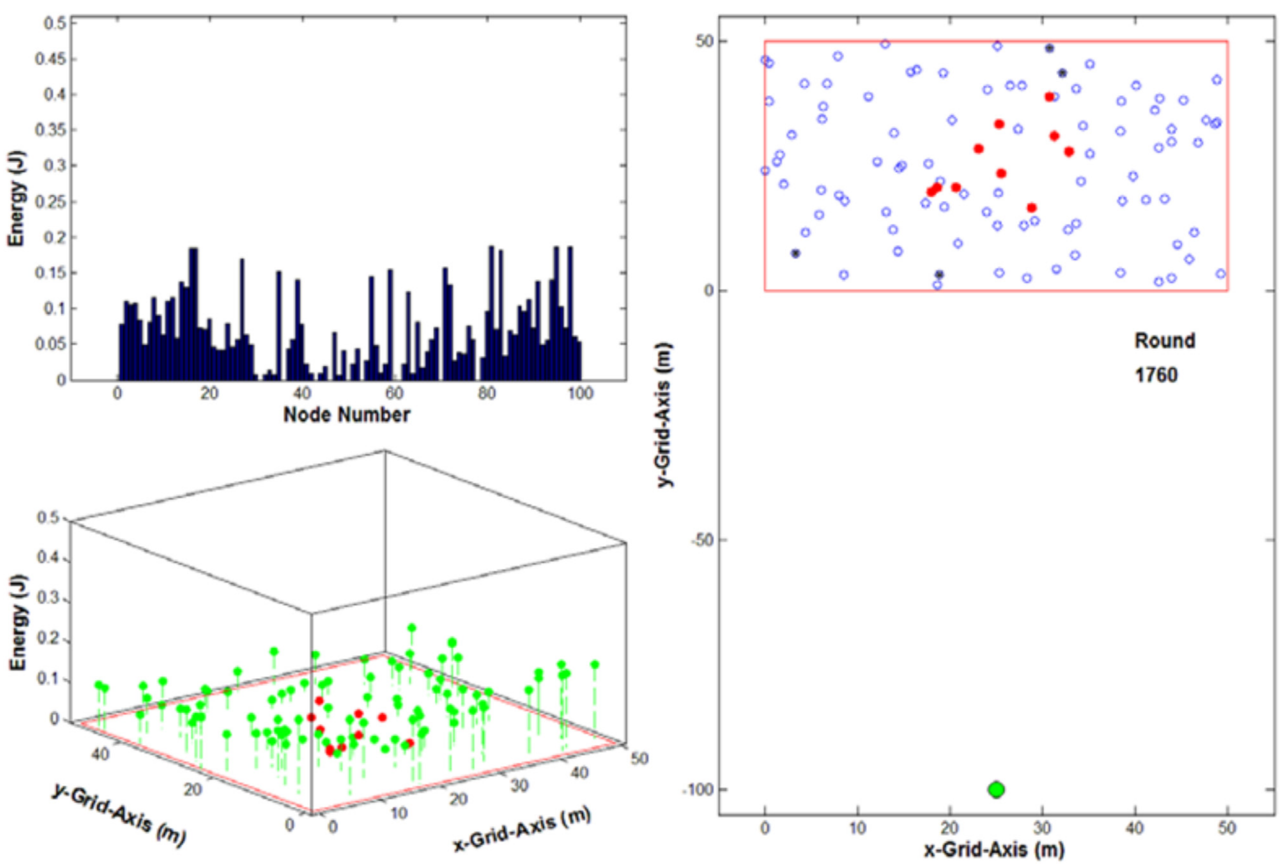

Fig. 3 LEACH routing in a single gateway tactical WSN illustrating the network topology when 10% of the nodes are dead.

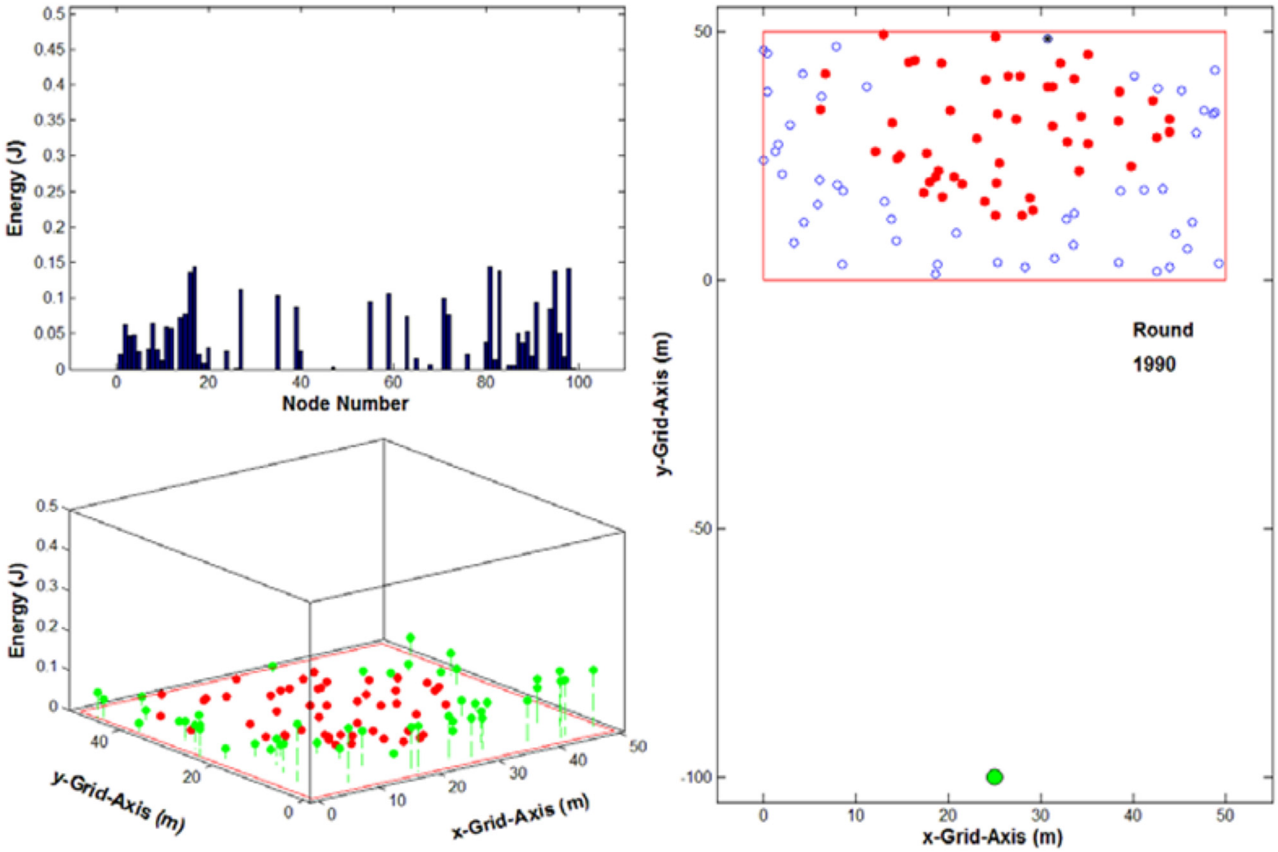

Fig. 4 LEACH routing in a single gateway tactical WSN illustrating the network topology when 50% of the nodes are dead.

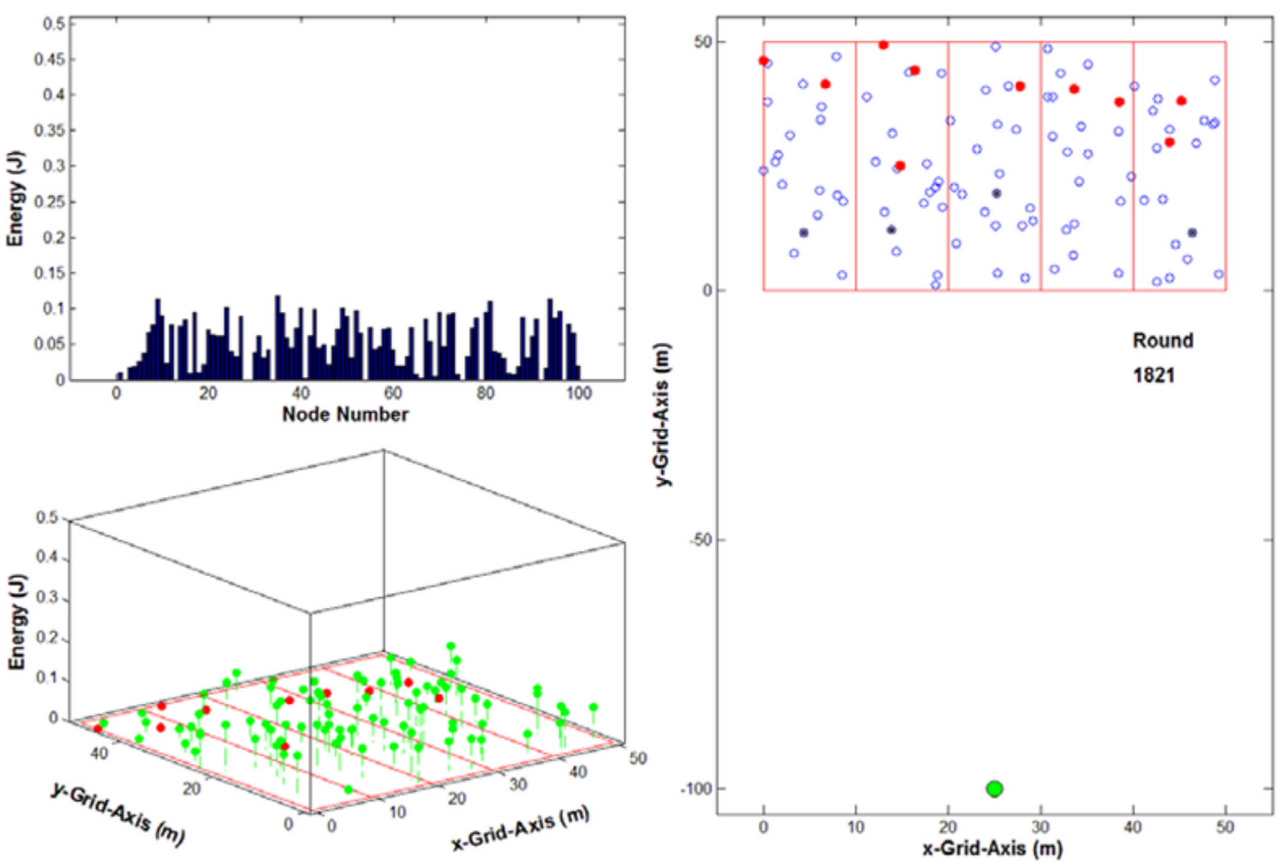

Fig. 5 Zone routing in a single gateway tactical WSN illustrating the network topology when 10% of the nodes are dead.

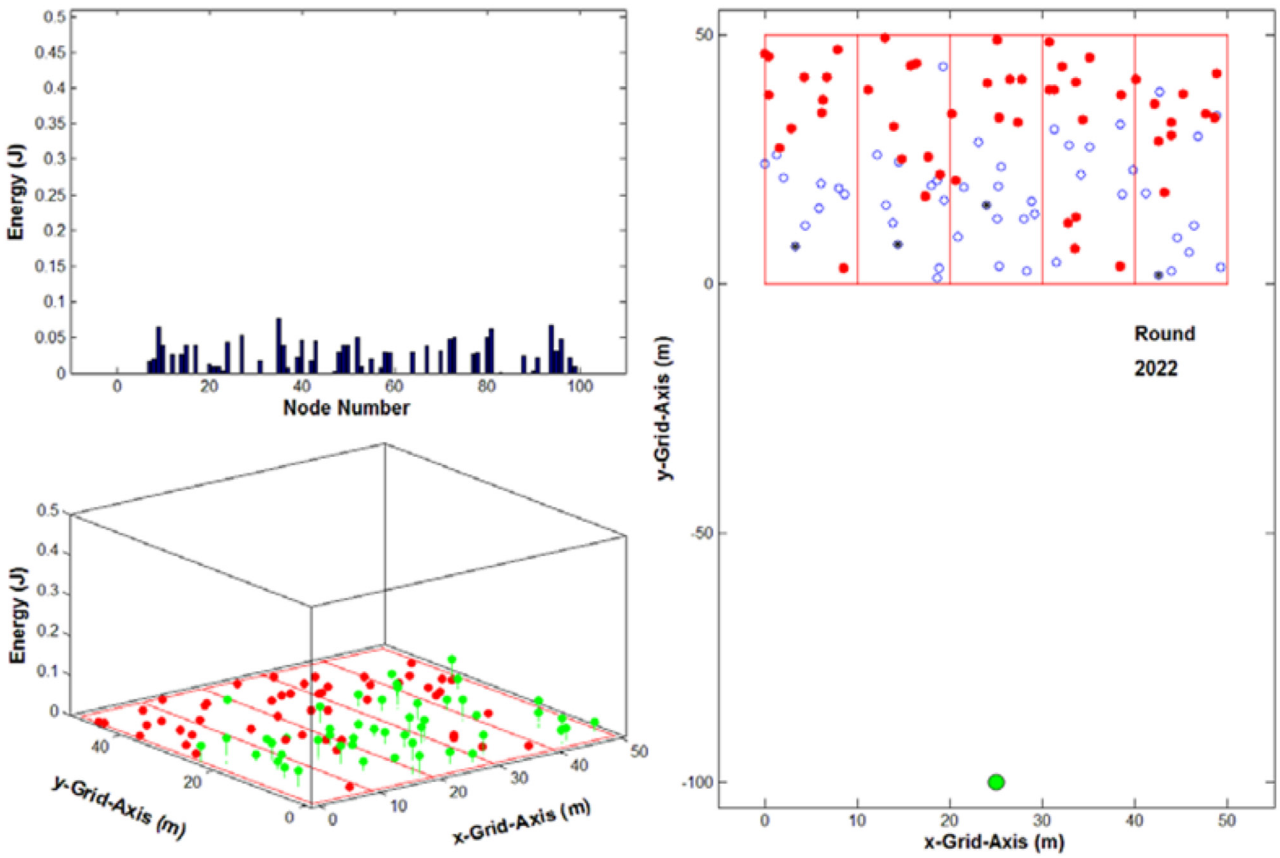

Fig. 6 Zone routing in a single gateway tactical WSN illustrating the network topology when 50% of the nodes are dead.

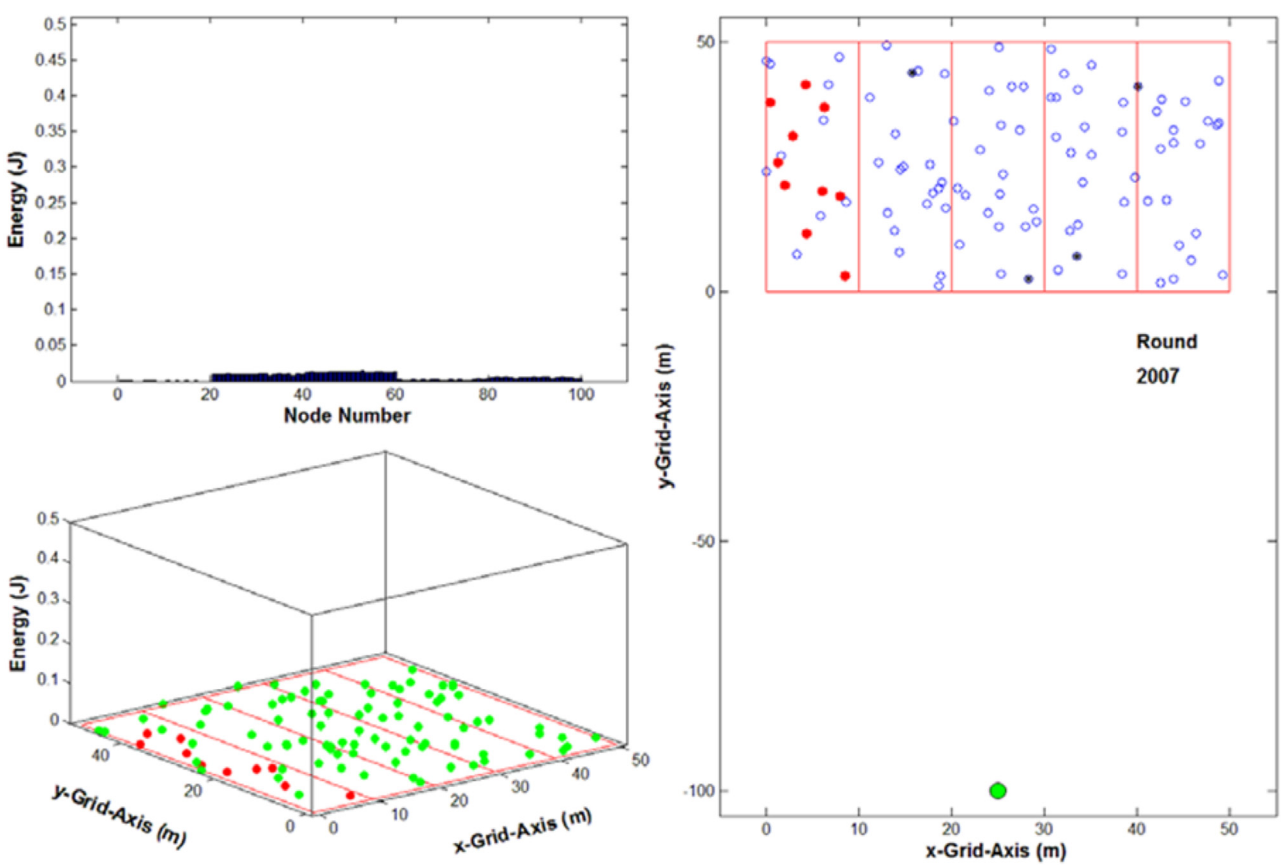

Fig. 7 EZone routing in a single gateway tactical WSN illustrating the network topology when 10% of the nodes are dead.

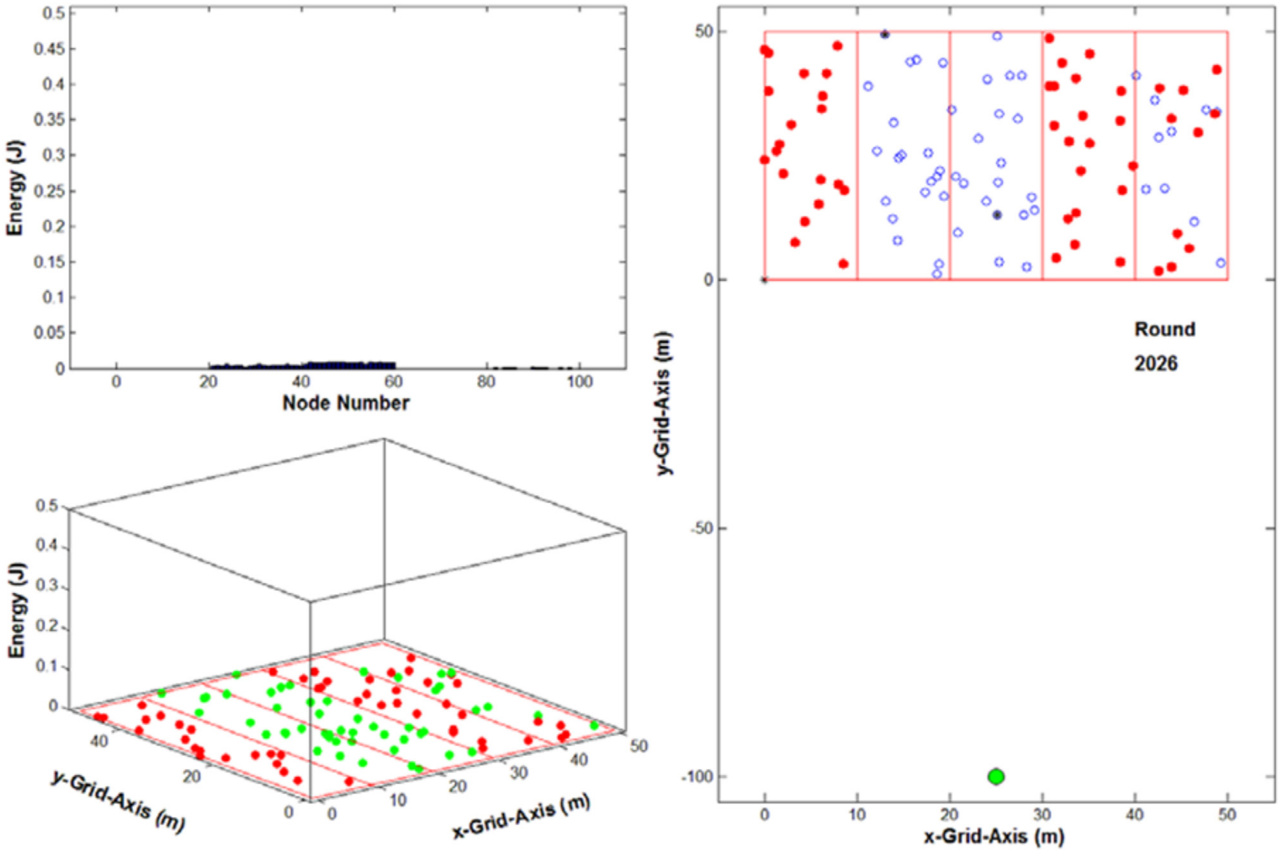

Fig. 8 EZone routing in a single gateway tactical WSN illustrating the network topology when 50% of the nodes are dead.

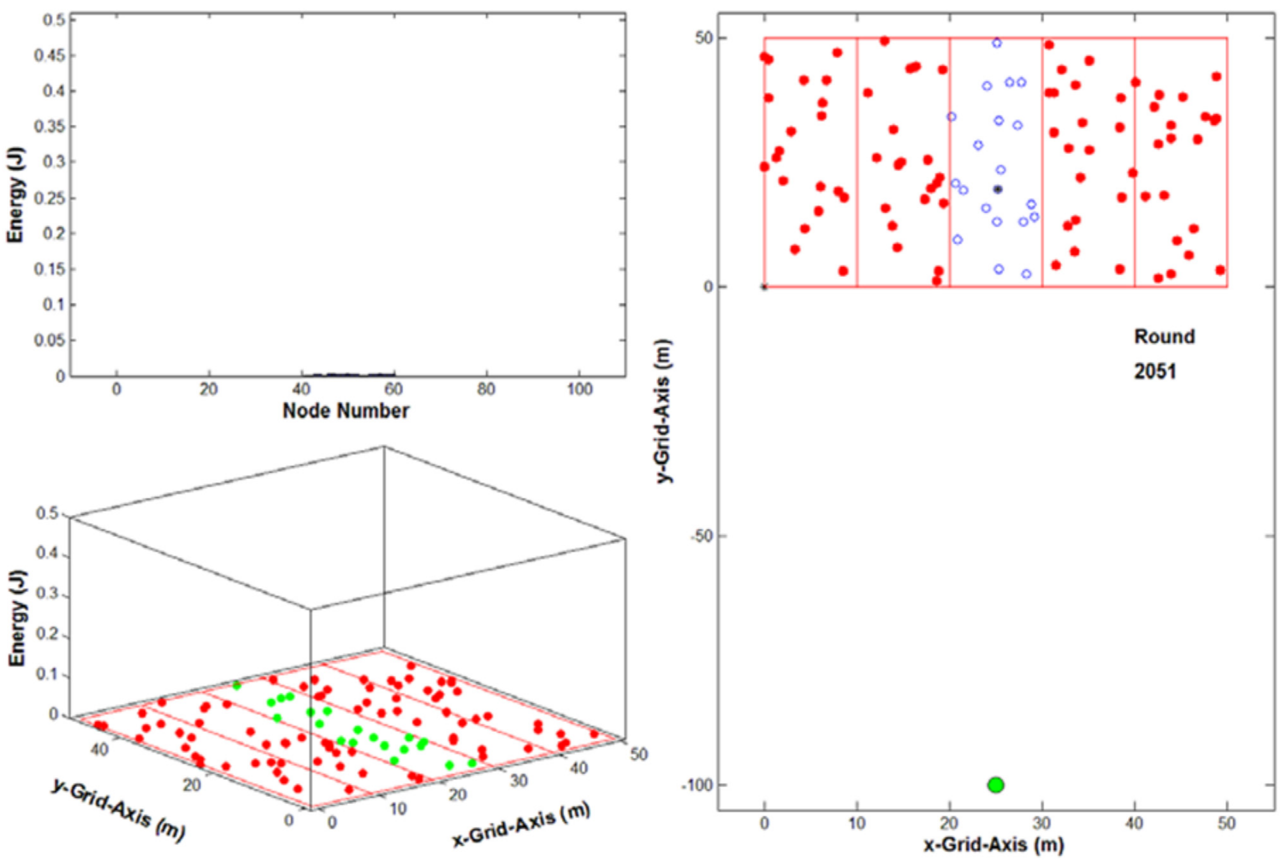

Fig. 9 EZone routing in a single gateway tactical WSN illustrating the network topology when 80% of the nodes are dead.

By restricting CH election criteria to choose the highest energy node in a zone, the energy level of all nodes in a common zone are uniformly preserved throughout the simulation and thus nodes die out evenly.

Notice in Fig. 9, the middle zone is 100% still in service even when all nodes in the other four zones are dead. This is a valuable consequence of the EZone algorithm. Even though 80% of the nodes are dead, the fact that one zone is still fully operational is significant for tactical operations; data sensed and transmitted within that middle zone will be sent to the gateway. Nodes within that middle zone have neighboring nodes that are still alive through which to transmit data. This ensures that the network remains valuable from a tactical perspective.

4.2. Comparisons of the algorithms based on energy consumption

We plotted the total tactical WSN system energy level during each transmission round (Fig. 10), the energy variance that resulted from the distribution of individual node battery levels (Fig. 11) and the number of live nodes during each round (Fig. 12). We visually observed how nodes geographically die out throughout the simulation. The results shown in Figs. 10-12 were obtained when 5000 different network topologies were simulated. Each routing algorithm was executed on each of the 5000 topologies and the average results are depicted in the figures. In each legend of Figs. 10-12, *S* after an algorithm name refers to the single gateway scenario, and *M* refers to the multigateway scenario. The variance is given by the following equation.

$$Var(E) = \frac{1}{n}\sum_{i=1}^{n}(e_i - \mu)^2 \quad (4)$$

where E is the random variable for energy, n represents the number of live nodes in the round, e_i is the energy of the ith live node in the round and μ is the mean energy for the round.

The clustering algorithms dramatically outperformed the MTE and direct routing algorithms. This is a result of rotating and distributing the high energy role of nodes that perform long-range transmission and data aggregation. The single and multigateway clustering algorithms generally displayed similar energy depletion rates that are illustrated in the linear regions of Fig. 10. The clustering algorithms decrease the energy variance of the tactical WSN, and our energy efficient zone routing algorithm, EZone, provided an indistinguishable flat variance plot compared to the other algorithms, as shown in Fig. 11. In Fig. 12 it can be seen that EZone increased the time when all nodes are alive, with the single gateway EZone simulation outperforming all the other algorithms.

Our EZone algorithm outperformed all other algorithms from a topology perspective during node die out as well. While the algorithms created a pattern for die out, our energy efficient algorithm kept all nodes in one area/zone alive for the longest time possible. Node dies out of the other routing algorithms occurred in an unfavorable fashion. For example, in the direct case, live nodes farther from the gateway died first since their energy is depleted proportional to their distance from the gateway. As a result, areas farthest from the gateway lost service first, while areas closest to the gateway remained in service longest. In MTE routing the nodes closest to the gateway died first. The LEACH algorithm inefficiently creates clusters that cause the network to die out starting in the center of the sensor field and progressing radially outward. As a result of this die out mechanism, we lose coverage in the middle of the sensor field first. These dying out mechanisms warrant the

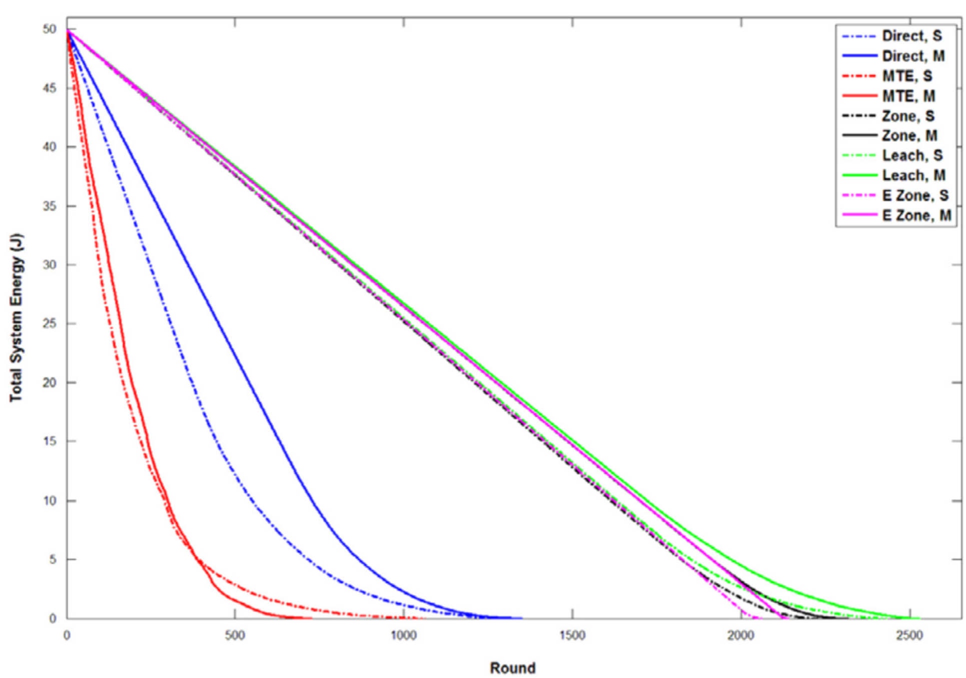

Fig. 10 Total tactical WSN system energy versus transmission round for direct, MTE, LEACH, zone and EZone routing algorithms in single gateway and multigateway scenarios.

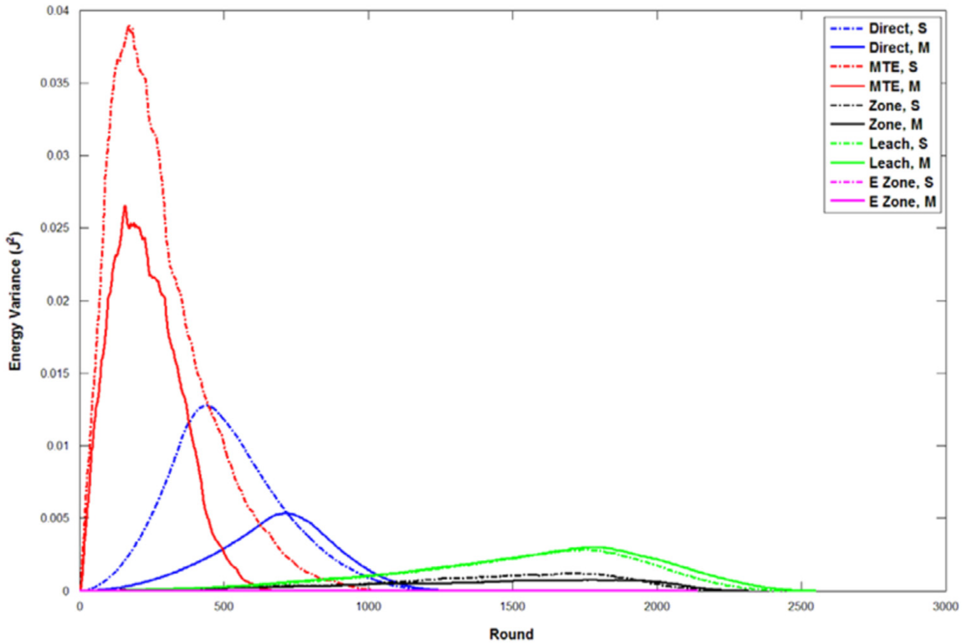

Fig. 11 Energy variance versus transmission round for direct, MTE, LEACH, zone and EZone routing algorithms in single gateway and multigateway scenarios.

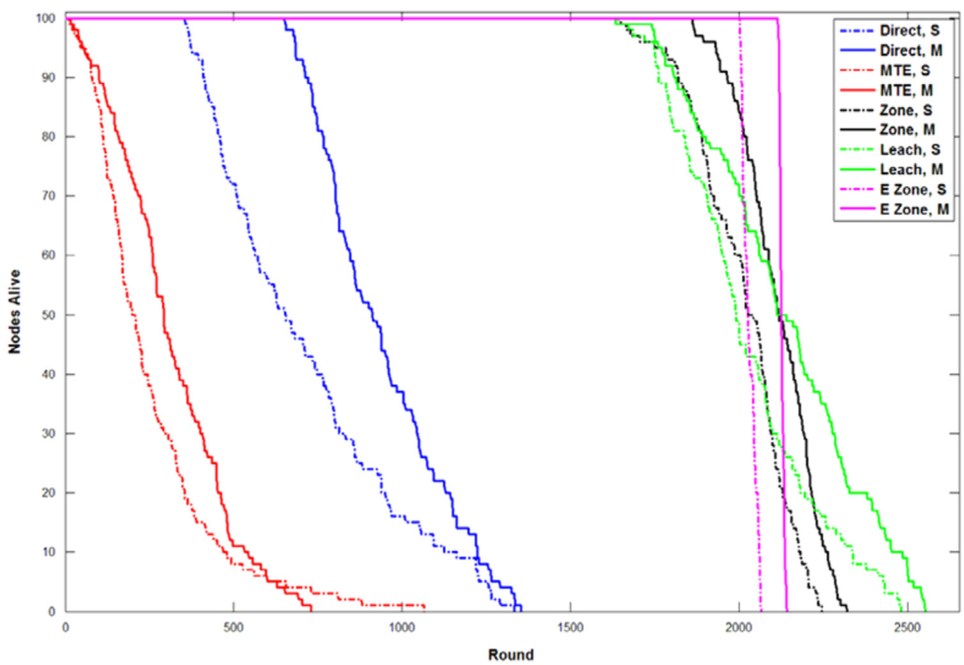

Fig. 12 Total number of live nodes versus transmission round for direct, MTE, LEACH, zone and EZone routing algorithms in single gateway and multigateway scenarios.

choice of EZone for a tactical WSN since it preserves 100% network coverage the longest time for specific zones.

The addition of another gateway was most significant in the direct and MTE algorithms as the energy variance is lowered by approximately 50 percent. This can be seen in Fig. 11. The energy variance of the zone routing algorithms were both lower than LEACH, with the single gateway scenarios performing better than LEACH in a multigateway configuration. In Fig. 12 we can see that the EZone-S and EZone-M plots keep 100% of the nodes alive until approximately rounds 2100 and 2200, respectively, and then there is a significant drop in the number of nodes alive. In comparison, the LEACH-S and LEACH-M plots show that 100% of the nodes are alive until approximately round

1800 but there is a more gradual drop off in the number of nodes alive. This supports our assertion that EZone offers the most time with all nodes alive whereas LEACH offers the most time with at least one node alive.

This is an important distinction, particularly when dealing with tactical operations. While having at least one node alive may be useful in commercial WSNs, it is not practical for WSNs deployed for tactical operations. With one node alive, there is very little that can be done, unless the node is very close to the gateway. Even if more than one node is alive, the possibility of having nodes alive in different areas of the network that are not connected is also not helpful in tactical operations. Thus, EZone's ability to keep all nodes alive for a longer period of time than LEACH combined with its ability to keep all nodes within one zone alive (see Fig. 9) makes it more applicable for use in tactical networks.

5. Conclusion

Tactical WSNs are used by the military to obtain information about ground situational awareness. This information facilitates tactical decision making. In order to increase service life in various areas of a tactical WSN, we need to control the network topology such that nodes with residual energy are used and maintained for continuing communication. We develop an energy efficient zone routing algorithm, called EZone, to tactically control the network topology by providing 100% service life of all nodes in specific zones/ areas of the network for a longer period of time when compared to other energy aware routing schemes, in particular LEACH. Our EZone algorithm offers the best opportunity to extend tactical WSN service life while maintaining tactical control of the network in both single and multigateway configurations. It produced the least variance in energy distribution at any round and smartly balanced cluster and node traffic balancing to decrease energy consumption.

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